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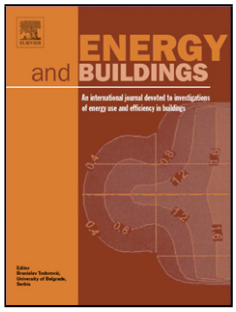
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Methodological framework for assessment of energy behavior of historic towns in Mediterranean climate

Mariella De Fino *[a], Alba Scioti [a], Elena Cantatore [a], Fabio Fatiguso [a]

* Corresponding author: fabio.fatiguso@poliba.it

[a] Department of Civil, Environmental, Territory and Building Engineering and of Chemistry, Polytechnic of Bari, Bari, Italy

Abstract

Within on the ongoing international debate on methods and tools that might help include the built heritage as strategic target within the policies for NZE buildings, the paper develops a methodological framework for performance assessment and control of historic buildings and districts in coastal and sub-coastal towns of South Italy, as specific geocluster of Mediterranean traditional architectures.

In detail, based on the environmental, architectural and constructional investigation at different scales, the definition of some building-types is proposed, as descriptive models that might support the identification of energy deficits, building pathologies, inherent bioclimatic qualities and historical-architectural values, as well as the selection of effective and compatible intervention strategies within scenarios of integrated building refurbishment and urban regeneration of homogeneous areas.

The application to two representative case studies details the operation phases and the achievable results toward the validation of the general methodology. Particularly, the study highlights how the energy improvement of the built heritage should focus on innovative products and solutions (e.g. aerogel, PCMs, ..) that might guarantee the challenging and desirable balance between improvement of performances of building systems and safeguard of formal and material original features, as a compromise between prescriptive accomplishment and acritical exception of the normative standards.

Keywords: energy assessment; energy retrofitting; Mediterranean historic buildings; building-types.

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1. Introduction

The promotion in the construction sector of the efficient exploitation of energy resources on the road to decarbonisation has been for some years a key aspect in cultural debates, institutional policies and market trends at international level. According to the International Energy Agency (IEA), taking into account the dramatic incidence – about 30% - of building products and processes on global impacts and consumptions, a virtuous framework of codes, plans and investments has been developed worldwide, with double interventions in 2014 compared with 2009. Particularly, based on the main development tendencies, the interventions have concerned the construction of new buildings in countries like China and United States or the refurbishment of existing buildings in countries like Germany [1].

In fact, compared with the American and Asian contexts, the European Community, where the annual rate of new constructions for the residential sector is about 1% [2], has strongly promoted in the Member States several measures and actions toward the energy retrofitting of the existing building stock. Particularly, within the European buildings, which are responsible, according to the Buildings Performance Institute Europe (BPIE), of 40% of energy consumptions and 30% of greenhouse emissions in the sector, a great share, about 75%, comes from residential buildings. As a result, the Directive 2012/27/EU on Energy Efficiency points out the need to "*establish long-term strategies […] for the renovation of the building stock*", which "*represents the single biggest potential sector for energy savings*". Similarly, the Directive 2010/31/EC on the Energy Performances of Buildings promotes the development of "*policies and measures such as the setting of targets in order to stimulate the transformation of buildings that are refurbished into Nearly Zero-Energy Buildings*" [3]. Such recommendations have been adopted in Italy too: according to the National Agency for new Technologies, Energy and Sustainable Economic Development (ENEA), national energy retrofitting actions have greatly concerned the residential sector, with about 2.5 millions of investments from 2007 to 2015 [4].

If the energy retrofitting of the existing buildings, particularly in Europe, has been undertaken though several programs, tools and applications, historic architectures and urban districts are still at the centre of attention by the scientific community. In fact, the EU prescriptions and relative national transpositions make an exception for them, due to the recognized challenge to conciliate transformation requirements and conservation principles [5]. For instance, the above-mentioned Directive 2010/31/EU, while focusing on "existing buildings, building units and building elements that are subject to major renovation" on the pathway toward NZEBs rule out "*the buildings officially protected as part of a designated environment or because of their special architectural or historical merit, in so far as compliance with certain minimum energy performance requirements would unacceptably alter their character or appearance*".

However, the exclusion of the historical-architectural heritage from the current efforts toward energy efficiency targets might trigger a dramatic loss of economic value for a great share of the real estate assets – in Europe 23% of buildings

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was built before 1945 [6]. Moreover, such a loss might affect the physical and functional obsolescence and environmental

and social decay that are already quite severe – only in Italy 50% of buildings older than 70 years show poor state of conservation [7].

Within such a scenario, several studies [8] and projects [9] by universities, research centres and innovative SMEs, as well as some documents by government institutions and associations, at national [10] [11] and international [12] [13] levels, have been released. They all share the purpose to provide with guidelines and best practices for the selection of suitable energy retrofitting solutions for the historical-architectural heritage.

In detail, the review of the state-of-the-art highlights some common topics in the cultural and scientific debate. Among them:

- Centrality of the context, which is not only the geographic-environmental background, but, according to the concept of "geo-cluster", a "transregional area with strong similarities in terms of climate, culture, behaviour, construction typologies, technological solutions and available products", in order to address the processes to the specific features of the local territory and community [14] [15] [16].
- Assessment of the actual behaviour of the fabric, based on direct investigation, in order to carefully define residual performances and, thus, effective and low invasive interventions [17] [18] [19] [20] [21].
- Identification of benchmarking categories for ex-ante assessment and ex-post control, given that the historic built heritage, despite its heterogeneity and variety, shows some recurring architectural, constructional and functional characteristics for specific building typologies and ages [22] [23].
- Enhancement of inherent bioclimatic qualities for air and heat passive control, which features the traditional architecture [24] [25] [26].
- Joint application of traditional and highly innovative retrofitting techniques in order to guarantee compatibility, reversibility and efficacy of intervention [27] [28].

According to the above-mentioned topics, the authors have carried out in the last years several studies, as methodological and operational contribution to the debate on the energy assessment and retrofitting of the built heritage, with specific focus on historic districts in Mediterranean climate. Particularly, methods, tools and solutions have been targeted on the envelope components, taking into account that they mainly address the challenging balance between improvement of performances and safeguard of formal and material features of the fabric, compared with still relevant energy factors – e.g. plant facilities, users' behaviour, consumptions' monitoring and control [29][30][31] [32].

1.1 Aim of the research

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The main goal of the research concerns the definition of a methodological framework, in terms of investigation tools, assessment criteria and intervention paradigms for the energy improvement of the historic envelope, both in terms of "passive" behaviour and integration of "active" systems from renewable energy sources.

In detail, the general methodology, as described in section 2, is herein validated on two representative case studies of the coastal and sub-coastal towns of South Italy, as thoroughly investigated in section 3. Specifically, the validation has concerned the improvement of the thermal performances of the construction components, taking into account the Italian normative thresholds for "non-historical" existing buildings, as released after the Directive 2010/31/EC, in order to assess their feasibility for such a delicate domain, as reported in section 4. Thus, the identification of suitable solutions is carried out, in terms of design interventions in section 5, in terms of effective, compatible, low-invasive strategies for future installations that might include the built heritage within the NZEBs vision through balanced goals between prescriptive accomplishment and acritical exception of the normative standards.

2. Methodology

The proposed methodology for energy assessment and retrofitting of the built heritage has been elaborated within a national research project[1] and, then, developed and validated for the historic districts of the coastal and sub-coastal towns of South Italy, also by a regional funding program[2].

In detail, based on the state-of-the-art review and on the well-established structure of the refurbishment process for the built heritage – including analysis, diagnosis and intervention –, the methodology (Fig. 1) introduces some specific aspects, phases and goals for the topics of interest.

Particularly, the analysis phase concerns the systematic investigation of the entire historic town (A), according to several aspects – environmental, architectural and constructional – and different scales – from the urban settlement to the building component. It aims at assessing the most recurring and representative characters of the built heritage, in terms of inherent features and relationships with the surroundings, in order to identify a limited number of "illustrative" building-types (B), as categories where the totality of the "real" buildings might be assigned. Thus, the following diagnosis should concern only the building-types (C), by performance-based models and parameters, supporting the assessment of both transformation/improvement necessities and conservation/enhancement opportunities toward the definition of suitable strategies (D). Such strategies, developed for each building component, are conceived as design guidelines and best practices to be translated in the selection of technological solutions (E), based on both traditional and innovative products and systems for energy efficiency. Finally, the technological solutions might be replicated for

[1] Italian Ministry of Education, University and Research - Research Project of National Relevance: "Geo-cluster based innovative methodologies for energy retrofitting and performance improvement of the existing building stock (Partners: Politecnico di Milano, Politecnico di Bari, Università degli Studi della Basilicata, Università degli Studi di Catania, Università degli Studi dell'Aquila).

[2] Fondazione Cassa di Risparmio di Puglia – Research Project: "Methodological framework for assessment of energy behavior of historic towns in Mediterranean climate" (Scientific Coordinator: Prof. Fabio Fatiguso, Politecnico di Bari).

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all the “real” buildings corresponding to a certain “illustrative” building-type. Moreover, they should be applied in connection with further measures for functional and structural retrofitting, according to an integrated building refurbishment vision (F), as well as within territorial development scenarios toward the overall regeneration of homogenous urban/building areas (G).

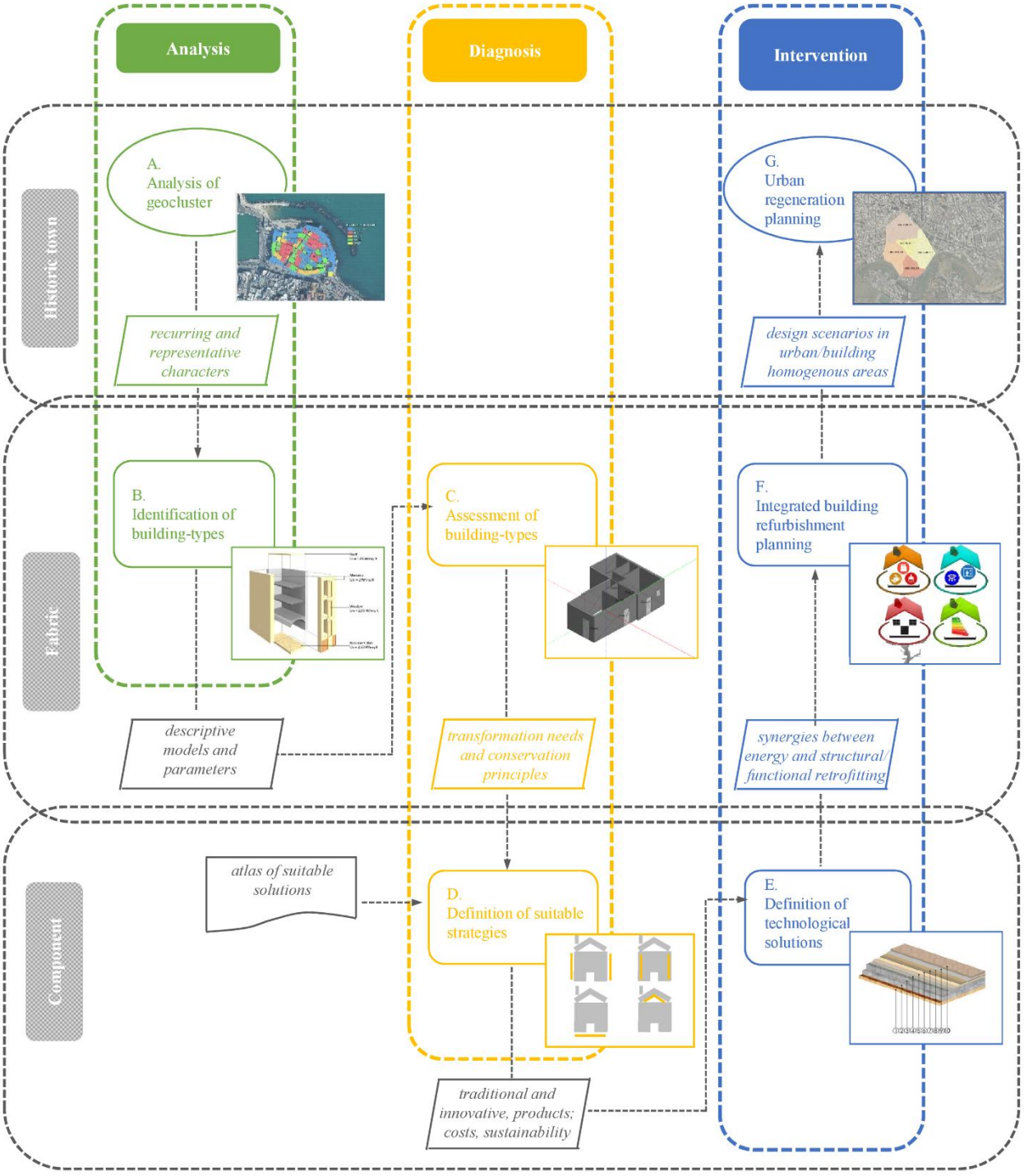


Fig. 1 General methodology

In all, the proposed methodology follows a scalar approach. The analysis and diagnosis proceed from the general to the specific, in order to achieve meaningful and representative results and contain assessment methods and tools on a

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limited set of cases. On the opposite, the intervention phase goes from the specific to the general, in order to promote integrated and structured actions, which might ensure the most favorable technical congruence, logistics management and optimization of time and resources within the overall requalification and regeneration strategies.

As far as the specific areas, tools and results are concerned, the phase A for the analysis of the geocluster (Fig. 2) is based on archivist and bibliographic records, direct survey, as well as on software-based simulations for data georeferencing and analysis of outdoor environmental parameters. It concerns the site for geographic-climatic peculiarities; the district, in terms of historical evolution, urban development, morphology and architecture; and an extensive sample of buildings for assessment of functional-typological characteristics, envelope construction materials and techniques, decay patterns and technological facilities.

All the above-mentioned aspects are elaborated as thematic maps, summary reports, drawings and schemes according to pre-set checklists and forms that ensure the achievement of consistent and comparable data, even for different geo-clusters. From the data analysis, the phase B (Fig. 2) is based on the classification of the entire built heritage under investigation in "illustrative" building-types, in terms of geometry, dimensions, orientation, functions and occupation profiles, surface finishing, opaque/transparent ratio, constructional and technological components, state of conservation. Such building-types are conceived as descriptive models. Particularly, according to the diagnosis purpose, they might be software-based simulation products for analytical assessment of the energy behavior of building systems and facilities. Furthermore, they might be explanatory categories of characteristics for phenomenological observations, referred to decay and failures (humidity patterns, surface deterioration …), inherent bioclimatic qualities (presence of cisterns, ventilation chimneys, courtyards …) or historical-architectural values (exposed stone facades, traditional floor tiles, original building components …).

Thus, the following phase C of diagnosis is focused on the building-types (Fig. 3) for the assessment of energy deficits and building pathologies, on the one hand, and the critical recognition of distinctive features of the original fabric, on the other hand. The above-mentioned areas merge in the phase D toward the definition of suitable solutions (Fig. 3), in terms of aware comparison between intervention priorities – for energy efficiency/sufficiency improvement and decay recovery – and degrees of transformability – for conservation and enhancement of the historical, architectural and constructional identity.

In order to support such a comparison, the methodology includes an atlas of pre-design solutions for each building component (Fig. 4), in order to identify possible transformation/adaptation schemes. The atlas is arranged in macro-areas, including energy increase of thermal resistance, increase of thermal inertia, upgrade/innovation of HVAC systems, upgrade/innovation of lighting systems, integration of photovoltaic systems, integration of wind-powered

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systems …). The schemes are decision-making databases to assess against the further requirements of conservation and enhancement of traditional surfaces, materials, techniques and spaces.

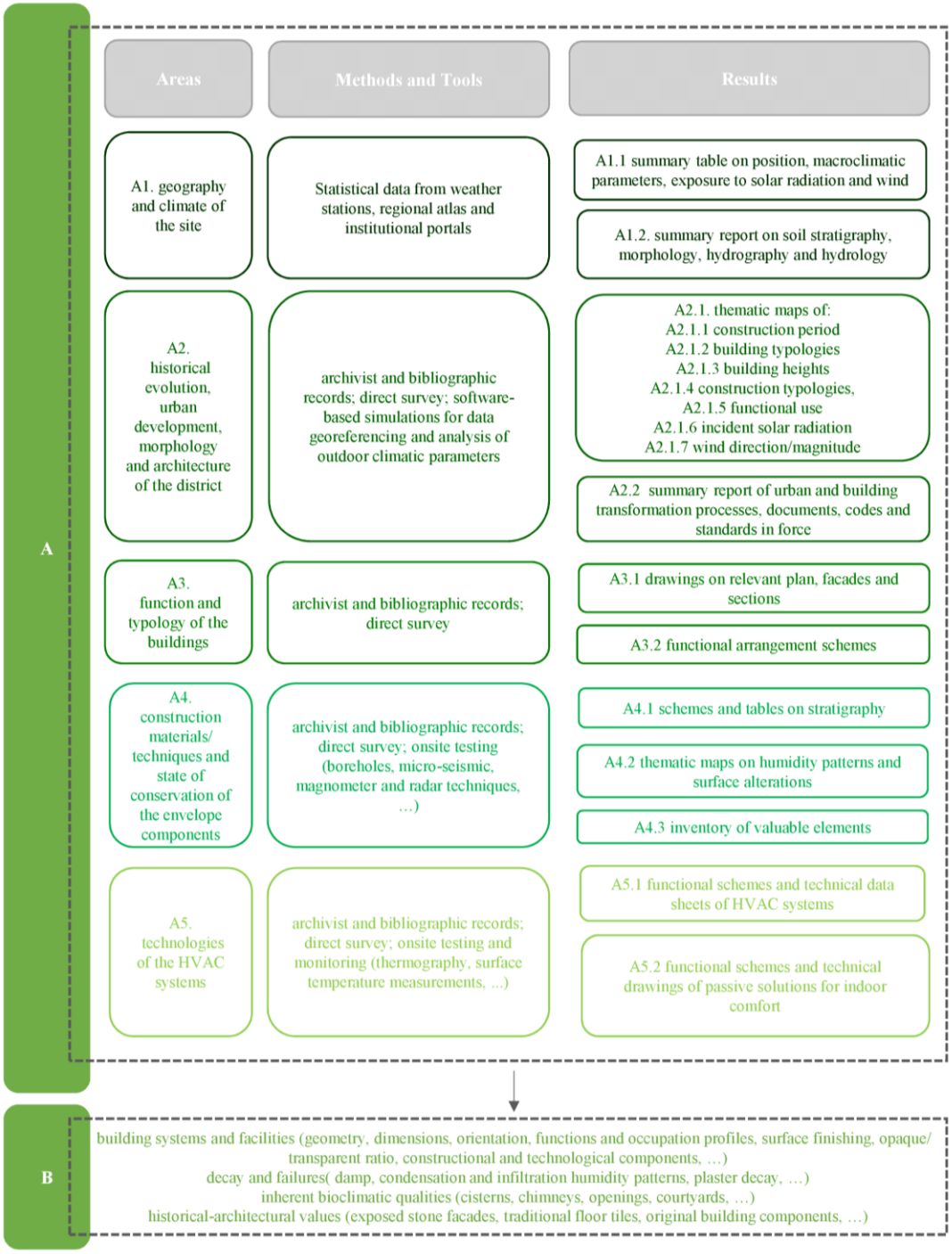


Fig. 2 Methodological phases A and B

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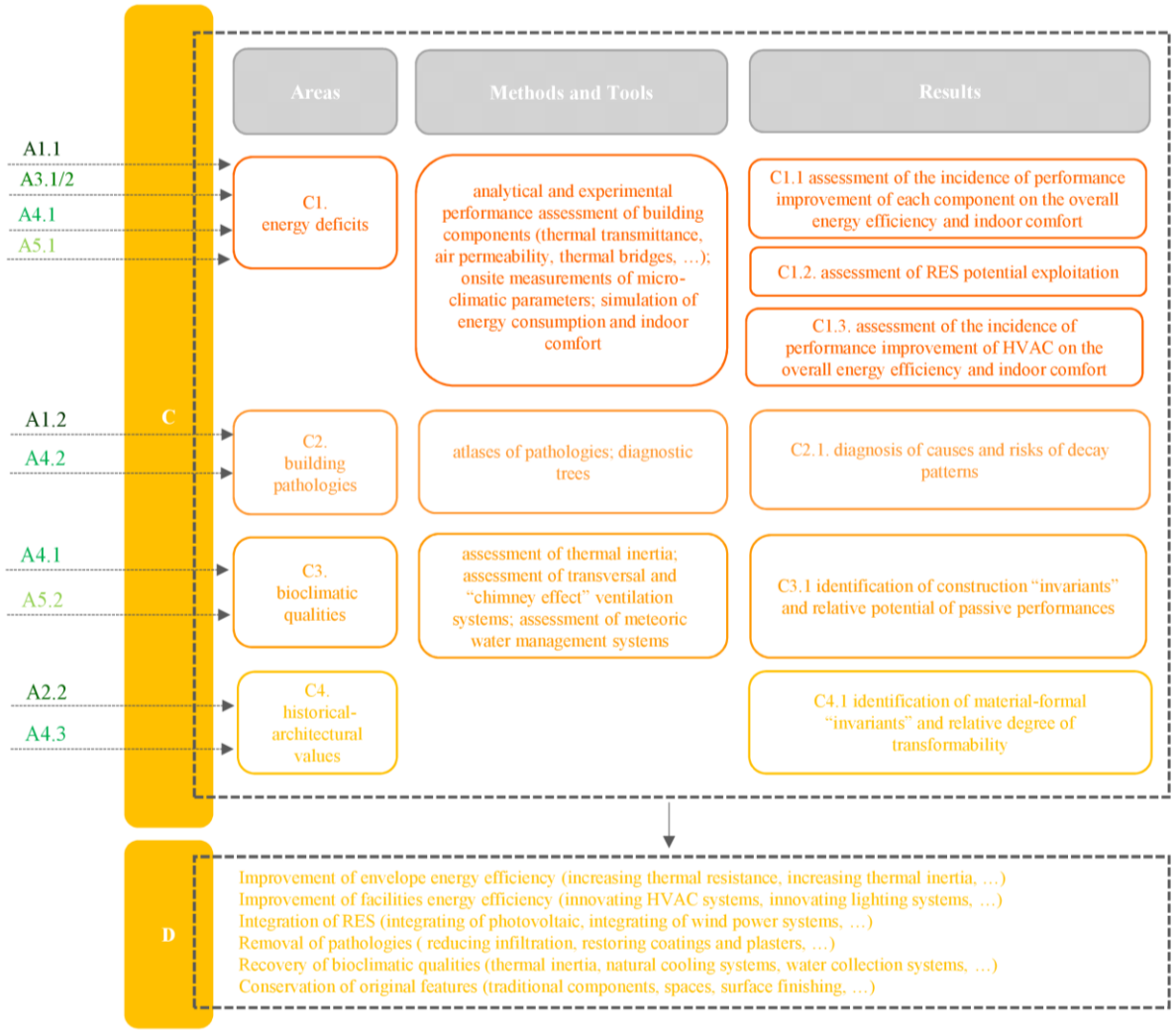


Fig. 3 Methodological phases C and D

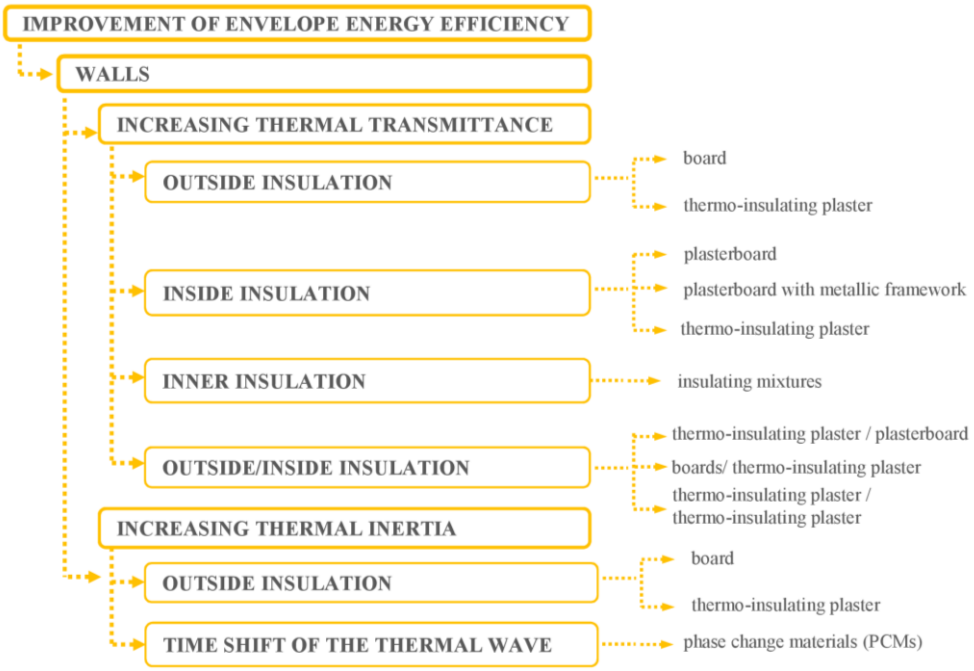


Fig. 4 Example of the structure of the atlas of suitable solutions

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The following phase E for the definition of technical solutions aims at transposing the schemes into design choices, in terms of products, systems and processes, eventually available on the reference market. Here, the selection is based on a holistic approach, taking into account technical reliability, material compatibility, architectural integration, functional congruence, as well as life cycle environmental and cost/benefit analyses.

It is worth mention that such an approach is particularly helpful for high-performing and cutting-edge products, since they are often still under testing, even in different fields, and require very careful performance validation.

Furthermore, a multi-criteria assessment of the technological solutions might support the identification of possible synergies among the energy retrofitting measures and further interventions for improving structural safety, use safety, accessibility and fruition of spaces and functions, according to an integrated building refurbishment vision, as in phase F. In detail, the integrated building refurbishment should be pursued according to a double perspective. From the one hand, the energy retrofitting might enable indirectly the overall performance improvement of the buildings, with regard to structural, functional and technological deficits either/or pathological and physiological obsolescence. On the other hand, it might be a driving force to initiate further actions, by turning a straightforward process of maintenance and restoration into a multi-faced strategy of controlled transformation and actualization of the built heritage, with respect for its values.

Finally, within phase G of urban regeneration planning, the interventions on the buildings should be integrated in territorial development scenarios. Such a process is facilitated by the proposed approach of analysis and diagnosis, because the technological solutions, as validated for the "illustrative" building-types, might be replicated for all the relative "real" buildings. Nevertheless, it should be further enhanced by the integration with wider urban quality strategies, with regard to energy grids, open public spaces, mobility and fruition, based on the recognition of homogenous urban/building areas. Here, the final goal is the continuity with the unitary nature of the historic towns, which are, despite their various evolution processes, the unique result of a continuous interaction among construction culture, environment, social changes and economic dynamics.

In the following section, in order to detail operation aspects and achievable results, the methodology is applied to two pilot cases, namely Monopoli and Maglie, as highly representative of the main typologies of old centres in Apulia Region, South Italy (Fig. 5). For the sake of shortness, the study is herein focused on the analysis and diagnosis phases, with specific attention to the envelope components.

3. The historic districts of Monopoli and Maglie: analysis of the context (A)

The first case, the Medieval district of Monopoli (Province of Bari) is emblematic of the Mediterranean historic coastal towns (Fig. 6), characterized by compact and dense urban arrangement and use of local calcarenitic limestone as construction material. More specifically, Monopoli, counting about 50.000 inhabitants, is located on the Adriatic Sea,

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approximately 9 meters above sea level and 40 km south of Bari, the main city of the Apulia Region. In the historic district, the blocks show high housing density with main fronts exposed along the NE-SW axis. In the near areas, even with good levels of compactness, the blocks are more distant with greater incidence of non-residential buildings.

The second pilot case is the historic district of Maglie (Province of Lecce), a paradigm of urban systems in the internal lowlands (Fig. 7), with wider arrangement of blocks and building tradition based on the calcarenitic tuff, namely "tufo Carparo". In fact, Maglie, 14.532 inhabitants and a maximum height of 81 meters above sea level, is located in the south central part of Salento, 29 km from the city of Lecce, in a nodal geographic position. The layout of the old town is characterized by a main axis around which the first urban aggregate has developed and secondary roads branch off.



Fig. 5. Maps of Italy and Apulia Region localizing the case studies, Monopoli and Maglie



Fig. 6. Aerial photos and street views of coastal historic towns in Apulia Region

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Fig. 7. Aerial photo and street views of Maglie

Herein, the main characters of the pilot-cases are described and mapped by ArcGIS (version 10.2), given that some more specific aspects, such as building pathologies, bioclimatic qualities and historical-architectural values, are reported for the building-types in the discussion of phase B, in paragraph 4.

3.1 Geographic and climatic peculiarities of the sites (A1)

The Monopoly territory consists of a flat coastal strip that rises quickly to the Murgia hills, reaching an average altitude of 408 meters, whereas the Maglie territory is located in the hinterland of the Salento plain, a vast and uniform lowland, with a height ranging from 78 to 105 meters.

Both towns have a general Mediterranean climate but with significant differences.

Maglie has mild winters and hot humid summers. Temperatures range from +5,6°C, average of the coldest month, to +29,6°C, average of the warmest month [33]. The precipitations are frequent in autumn and winter, while spring and summer are characterized by long periods of drought. The area is affected by the wind, both cold for the Balkans and hot from Africa.

Differently, Monopoly has warm-dry summers and mild-wet winters. Temperatures range from +6° C, average of the coldest month to +28,5°C, average of the warmest month [33]. The mitigating effect of the sea makes the temperature changes limited. Moreover, the winds are often breezes. The rainfall is concentrated in autumn and winter and has a very variable regime. In summer, the city is affected by the scorching heat waves coming from North Africa or from the mistral winds that can cause storms and sudden drops in temperature.

3.2 Historical evolution and urban development of the districts (A2)

The territory of Monopoli, inhabited since the Prehistory, was under the domination of Lombards, Byzantines, Norman-Swabians and Aragoneses that have influenced its anthropic characters throughout the centuries. The urban development was originally concentrated around churches and convents. Then, it extended all over the area bordered by the XVI century fortified walls where the Castle was founded. From the XIX century, the common process of extra-moenia expansion took place (Fig. 8).

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The territory of Maglie show an original nucleus dating back to the XIII-XIV centuries around the main road ad square ("Inner Island") and a later expansion in the XV-XVII centuries according to an elliptical arrangement ("S.Nicolò Island") with noble palaces, still present. In the XIX century, it became a key communication node in the area and extended according to a radial layout with neoclassical bourgeois residences and typical one-floor dwellings (Fig. 8).

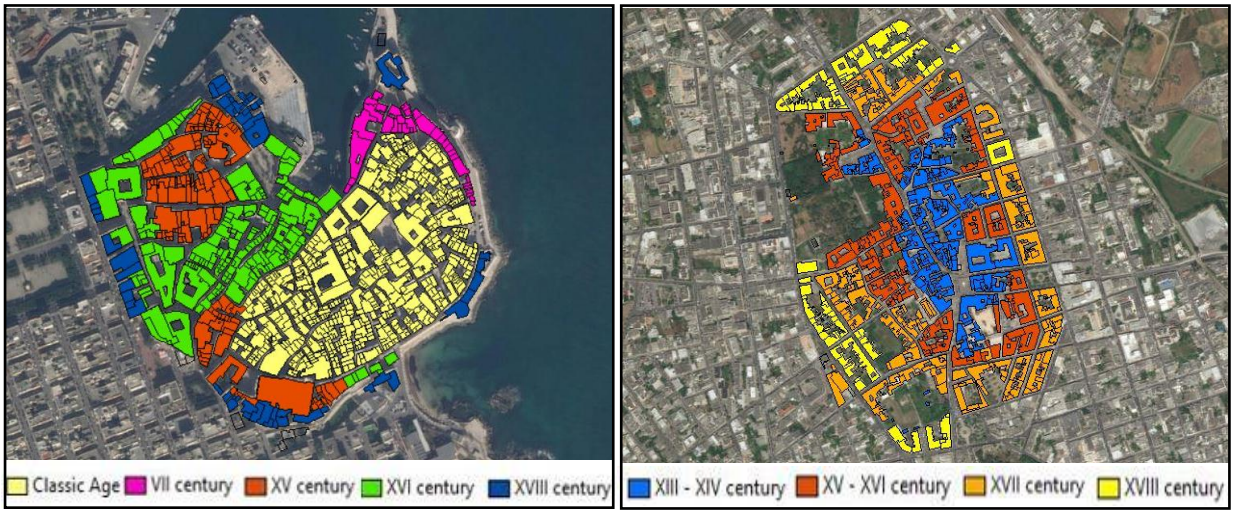


Fig. 8: Maps of historical evolution of Monopoli and Maglie old town

3.3 Building typologies (A3)

The typological analysis of the buildings has concerned the classification, in terms of functional use, functional layout, orientation and shading of the facades, building heights (Fig. 9 and Fig. 10) and building typologies (Fig. 11). Particularly, as far as the building typologies are concerned, five main categories have been identified that might be in turn further sub-classified for internal layout:

The *tower-house* shows a simple plan, with only one room per floor. It is two, three, four or five floors high with inner staircase. It is often aggregated in blocks where units are arranged in two symmetrical rows so that each unit has only one narrow external façade. The *palace-house* typically comes from the connection of two tower-houses. Therefore, it is featured by two rooms per floor on several floors. The *flat* is a multiple-room dwelling that occupies an entire floor of a building. The *apartment-block* is a building where each floor has two or more apartments. The *court-house* is featured by an internal courtyard, which might be private or public, with access from the street through an open atrium. All around the courtyard, several housing units are located.

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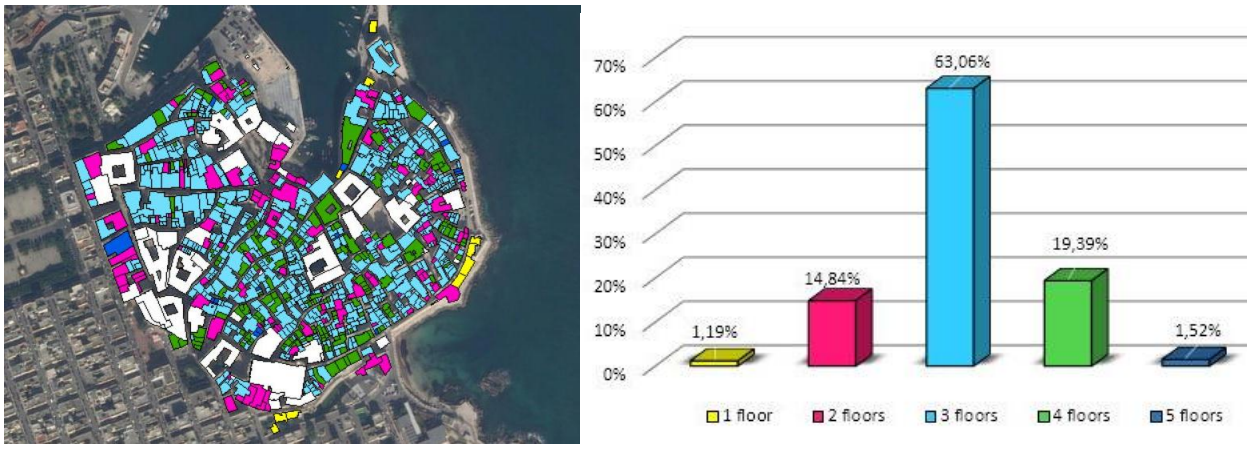


Fig. 9: Map and percentage distribution for building heights in Monopoli old town

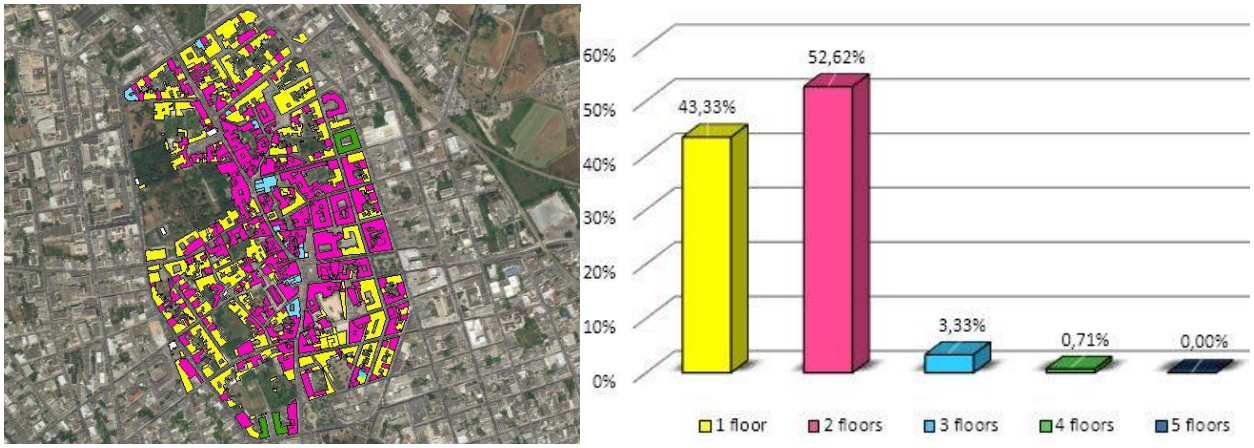


Fig. 10: Map and percentage distribution for building heights in Maglie old town

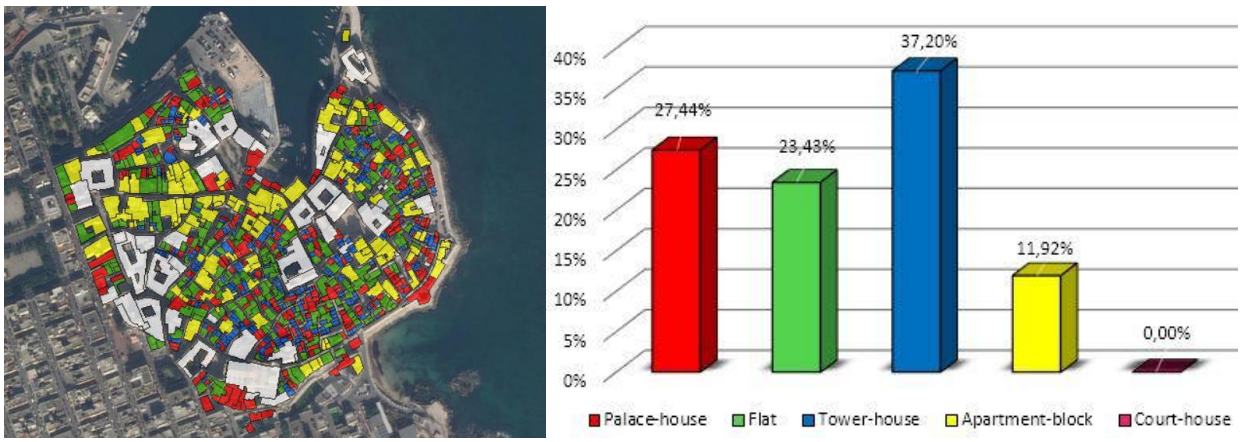


Fig. 11: Map and percentage distribution for building typologies in Monopoli old town

The tower-house in Monopoli and the court-house in Maglie were found as the prevailing typologies respectively.

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3.4 Construction materials and techniques (A4)

The historic urban settlements of the geocluster under investigation show quite similar construction materials and techniques, with specific territorial variants, due to the available local resources according to the pre-modern building tradition. In fact, the buildings have generally masonry load-bearing structure, with vaults, wooden slabs and, more recently, reinforced concrete slabs.

In detail, both the historic towns of Monopoli and Maglie were surveyed by research of historical-technical documents, mainly from archivist records and building development reports/plans of the municipalities, as well as by direct inspection and users' questionnaires for most accessible buildings.

Specifically, based on the overall survey, two main typologies of masonry structure might be identified in the pilot-cases. The former, in Monopoli, is featured by calcarenitic limestone (Fig. 12). The latter, in Maglie, is made out of "Carparo tuff" that is generally softer and lighter. Both typologies are 50-90cm thick. They might be exposed on the outer façade or covered by about 40mm thick plaster on both sides. They both are cavity walls with external leaves made out of squared blocks and inner nucleus filled with stone rough blocks and lime mortar. The cavity is generally more compact in Monopoli, whereas it might be even empty in Maglie.

In both cases, the basement slab is composed of stone tiles of different thickness on the soil. The roofs are generally flat in Monopoli (Fig. 13), mainly reinforced concrete or wooden slabs with stone tiles or, less often, cement tiles and waterproofing membrane. In Maglie, most roofs are stone vaults with "Cursi" stone tiles, which are arranged according to the vault extrados in some cases.

The intermediate floors are generally covered by the same typologies. In Monopoli, stone vaults cover the ground floor and wooden floors the upper floors. In Maglie, stone vaults cover all the floors. In both cases, windows show wooden frame and single-glazing or double-glazing, if recently replaced.

The assessment of the general state of conservation reveals great variability depending on the maintenance. However, most buildings show poor conditions, with cracks, damp patterns and surface deterioration.

3.5 HVAC technologies (A5)

As far as HVACs are concerned, despite some differences due to the occurrence of maintenance, some characteristics might be generalized: i) low-efficient lighting devices; ii) gas boilers and radiators for heating; iii) gas or electric boilers for hot water; iii) fan-coils for cooling only in Maglie.

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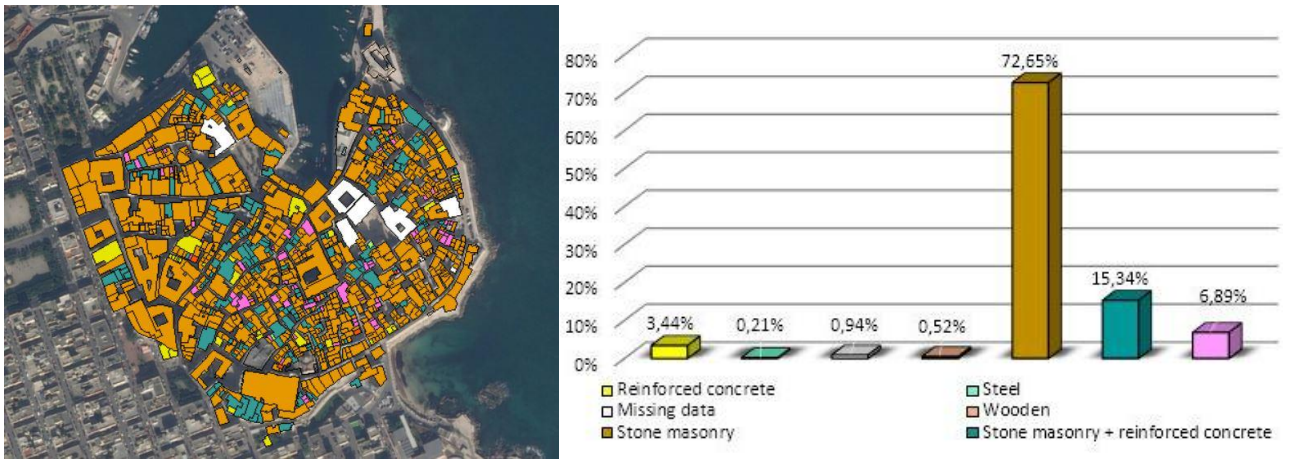


Fig. 12: Map and percentage distribution for vertical structures in Monopoli old town

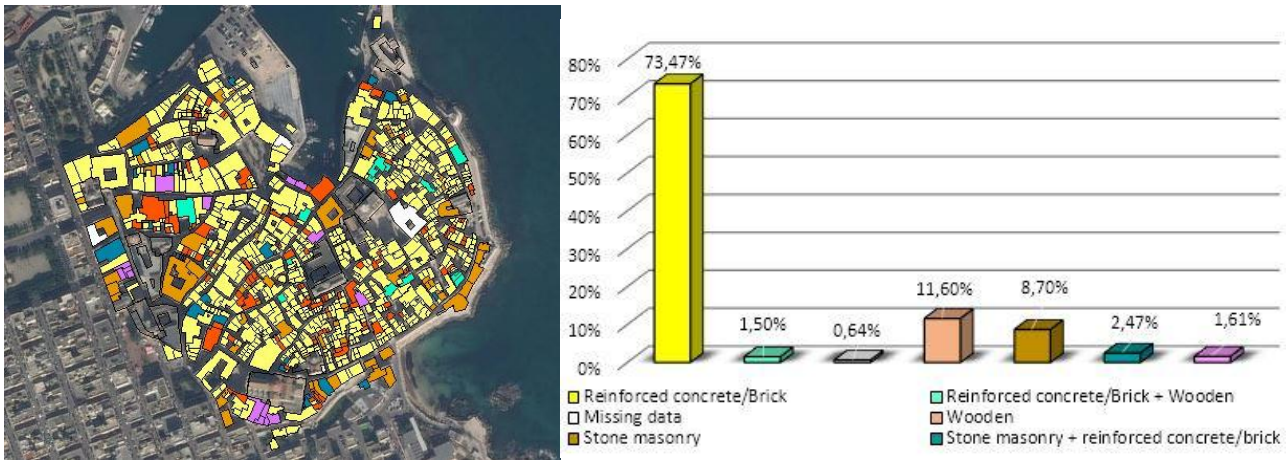


Fig. 13: Map and percentage distribution for horizontal structures in Monopoli old town

4. The building-types: identification (B) and assessment (C)

According to the methodology, as in paragraph 2, the analysis of the geocluster enabled the identification of the building-types, namely a limited number of "illustrative" models (Fig. 14), featured by recurring characters of the built heritage, as categories where the totality of the "real" buildings might be assigned.

It is worth mention that the direct survey of most "real" buildings made the selection of the characteristics of the "illustrative" models very reliable and representative.

In the case of the historic town of Monopoli, the most representative building-type is a tower-house, in the middle of a block, where units are arranged in two symmetrical rows. The plan is rectangular - 8m deep and 4m large -, with only one external façade and one opening per floor. The model has commercial use at the ground floor – 3m high – and three upper floors – 3.5m high - as one-family dwelling. The main construction materials and techniques are summarized as follows:

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- Masonry cavity walls (80cm thick) with inner nucleus of limestone calcarenitic stone, outer leaves exposed at the ground floor or covered by plaster (4cm thick) at the upper floors, internal leaves always covered by plaster (4cm thick);
- Windows with traditional wooden frame (115cm x 290cm x 40mm) and single glazing (0,3cm thick);
- Roofs with reinforced concrete/ hollow brick blocks (25cm thick) slab with lightweight concrete inclined screed, waterproof membrane and "Cursi" stone tiles;
- Stone barrel vault (20cm thick) between ground and first floor and wooden joists and board (18cm total thickness) at the upper floors.
- Basement slab with "Cursi" stone tiles (8cm thick) on soil, here assumed as wet due to sea proximity;

In the case of the historic town of Maglie (Fig. 13), the recurring building-type is a court-house, in the middle of a block. The plan is U-shaped, with one façade on the street (16,5m large), where the courtyard is reachable through an open atrium. The model is two-floors high (each 5,4m high) with commercial activities at the ground floor and three residential units at the first floor with internal staircases to access the courtyard. Under the courtyard, a cistern is located for water collection.

The main construction materials and techniques are summarized as follows:

- Masonry cavity walls (70cm thick) with inner nucleus of "Carparo" tuff, all the outer leaves exposed and all the internal leaves covered by plaster (4cm thick);
- Windows with traditional wooden frame (110 cm x 265cm x 40mm) and single glazing (0,3cm thick);
- Roof with "Carparo" tuff vault (20cm thick), upper filling of mortar and tuff aggregates (10cm), waterproof membrane and "Cursi" stone tiles following the vault extrados;
- "Carparo" tuff vault (20cm thick) between ground and first floor above the open atrium;
- Basement slab with "Cursi" stone tiles (8cm thick) on soil, here assumed as semi-wet.

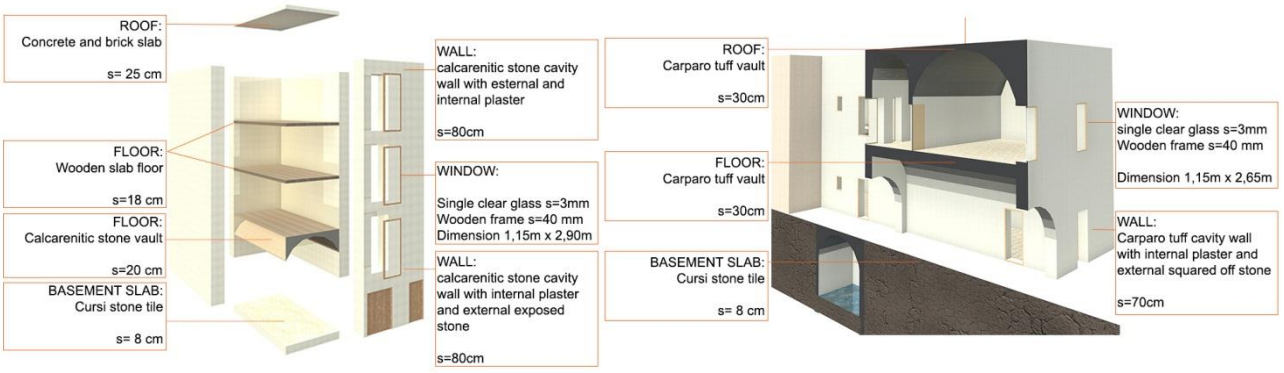


Fig. 14 Construction characteristics of the building-types characteristics (Monopoli on the left, Maglie on the right)

4.1 Energy deficits (C1)

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The assessment of energy deficits in the building-types, the tower-house in Monopoli and the court-house in Maglie respectively, was based on the above-mentioned identification of construction materials and components and carried out through dynamic simulations by Design Builder (version 4.7).

As a first stage, the assessment concerned the comparison of the actual thermal transmittances of each construction component against the Italian normative thresholds (D.I. 26th June 2015).

Tab. 1 shows the main comparison data that points out how all the components exceed the thresholds.

Table 1. Thermal characteristics of the models

\	Component	Thickness [m]	Current thermal transmittance [W/m^2 K]	Normative threshold [W/m^2 K]	Thermal transmittance difference [W/m^2 K]
Tower-house	Wall	0,80	1,493 [3]	0,38	1,11
	Roof	0,30	2,918 [4]	0,36	2,56
	Basement slab	0,08	3,797 [5]	0,40	3,40
	Window	-	5,4	2,40	3,00
Court-house	Wall	0,70	0,637 [6]	0,38	0,26
	Roof	0,30	1,351[6]	0,36	0,99
	1st floor ceiling	0,30	1,149 [6]	0,40	0,75
	Basement slab	0,08	3,65 [5]	0,38	3,27
	Window	-	5,4	2,40	3,00

Particularly, the most critical situations correspond to the concrete slab in Monopoli case and the basement slabs in both cases. Moreover, it is worth note how the "Carparo" tuff structures are more performing than the calcarenitic ones, due to the higher porosity of the construction material.

As a second stage, a sensitivity analysis was performed, in order to assess the contribution that the thermal improvement of each construction component gives to the overall heating and cooling consumptions of the building. For the purpose, a reference simulation was elaborated corresponding to the current configuration. Then, the thermal resistance of each component was increased independently and progressively. The overall idea was to estimate which component and to what extend mostly affect the energy consumptions if it is retrofitted singularly and not necessarily at the normative standards. Particularly, for the transparent components, two retrofitting simulations were assessed, corresponding to the replacement with double-gazed windows and low-emissivity double-glazed windows (thermal transmittance 3,3 W/m^2 K and 2,2 W/m^2 K respectively, where the threshold is 2,4 W/m^{2}K). For the opaque components, five retrofitting simulations were considered, corresponding to the reduction of the thermal transmittance of 20%, 40%, 60%, 80% and 100% of the difference between actual and normative values. The reduction of the thermal

[3] The thermal transmittance of a wall with similar characteristics was onsite measured

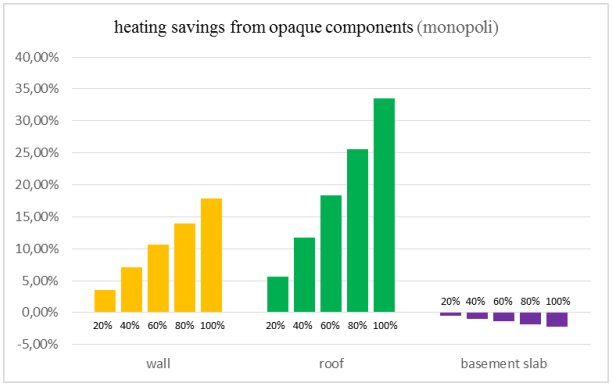
[4] The thermal transmittance was calculated based on the national code UNI 10351

[5] The thermal conductivity of the "Cursi" stone are reported in literature [34]

[6] The thermal conductivity of the "Carparo" stone are reported in literature [35]

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transmittance of the opaque components corresponded to the application of an insulation layer with increasing thickness on the external side. The inner design conditions were 20°C and 50% RH in winter and 26°C and 50% RH in summer. Figures 15-16-17 report the results of the iterative simulations.



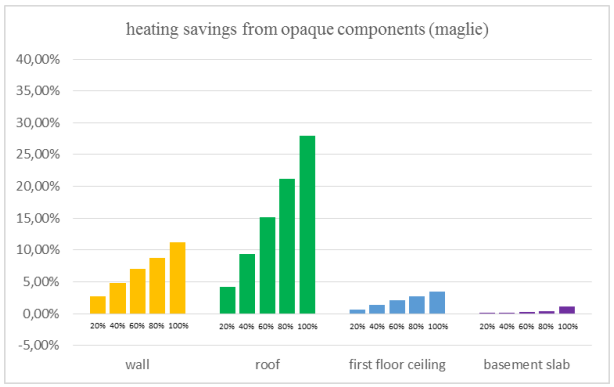
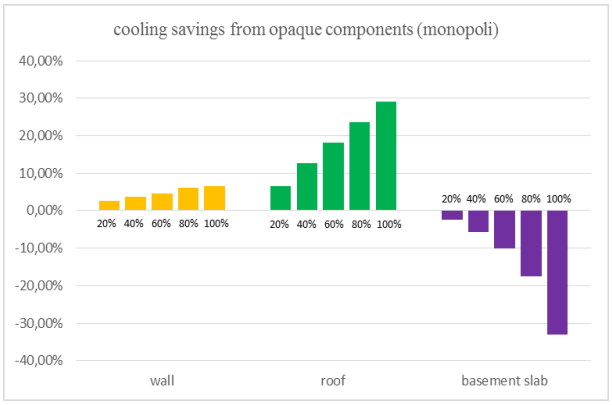
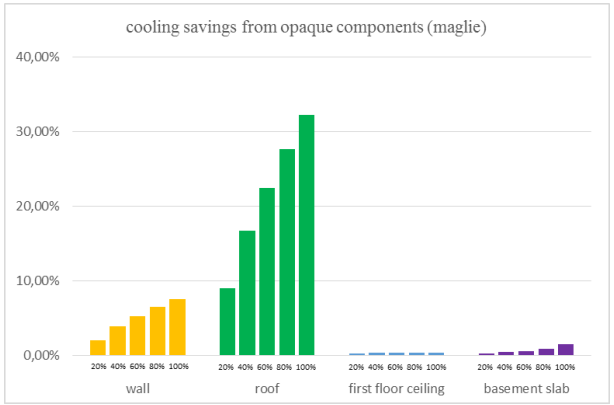


Fig. 15: Transmittance increase of opaque components vs heating saving in the case studies





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Fig. 16: Transmittance increase of opaque components vs cooling saving in the case studies

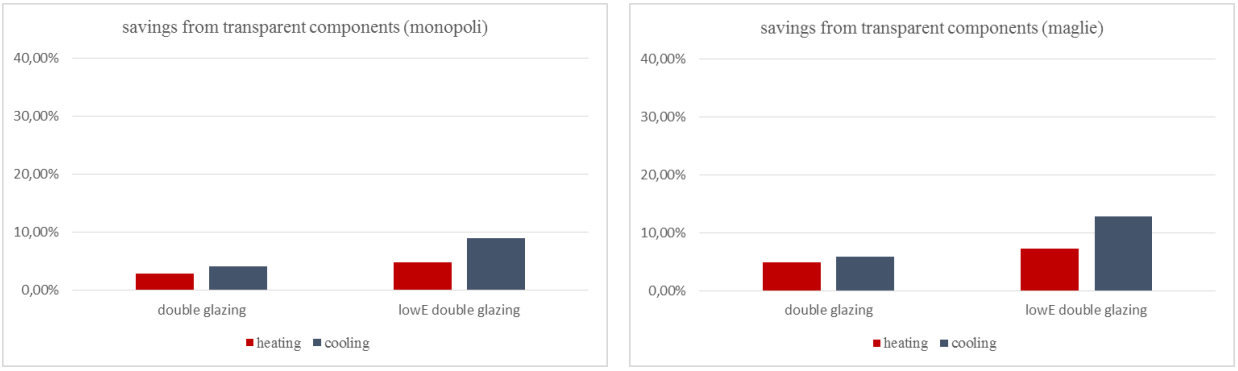


Fig. 17: Transmittance increase of transparent components vs heating and cooling saving in the case studies

It is worth underline that all the simulations were also elaborated with the same insulation layer on the internal side. Such a configuration was predictably worse, because the inherent thermal inertia of the component is neglected. In fact, it was found that, compared with the previous simulations, the heating consumptions increase of 1-2% on average and the cooling consumptions of 3-4% on average for each component at the normative threshold.

As far as the reported results are concerned, some general remarks might be outline.

For the tower-house in Monopoli, the components are listed below according to their incidence:

1. The highest incidence on the building energy consumptions comes from the roof, which, despite a limited area, shows the worst thermal performances in the current configuration. Moreover, it is the most exposed to the outer environmental agents (wind and rain in winter and direct solar radiation in summer) and, thus, to the variations of the external surface temperature. Such an incidence is relevant both in winter and summer (savings up to 33,5% for heating and 29,2% for cooling);
2. The walls play a prominent role in winter (savings up to 17,9% for heating), also because the facade is shaded by the surrounding buildings and does not benefit from the solar gain in the cold season. Differently, they do not provide a significant contribution in summer (savings up to 6,4% for cooling), because of the good thermal inertia even in the current configuration.
3. The basement slab shows an opposite trend on the consumptions compared with roofs and walls (increase up to 2,3% for heating and 33% for cooling), probably because the insulation layer would act as a thermal shield from the soil, which positively attenuates and shift the thermal wave and exhibits opposite temperature trends compared with the external air.
4. The windows are not really relevant both in winter and summer (savings up to 4,8% for heating and 9% for cooling in the case of low-emissivity double glazing systems that fulfil the normative standards). In fact, the transparent envelope is quite limited compared with the opaque one. Moreover, it is continuously shaded in winter, so that the solar gains are reduced in the cold season.

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For the court-house in Maglie, the following components were found as the most incident:

1. The highest incidence on the building energy consumptions comes again from the roof, which is here more performing in the current configuration, but still exposed to the outer environmental agents on a wider area. Such an incidence is relevant both in winter and summer (savings up to 28% for heating and 32,2% for cooling);

2. The walls show a similar trend compared with the case of Monopoli. However, their contribution is here less relevant, because of the better thermal properties in the current configuration (savings up to 12,8% for heating and 7,5% for cooling);

3. The basement slab provides with a negligible contribution both in winter and summer (savings up to 3,7% for heating and 1,5% for cooling). Here, even though the trend does not invert, probably because the soil is not considered completely wet, the insulation improves the thermal resistance, but inhibits the beneficial effects from the soil.

4. The windows are quite relevant both in winter and summer (savings up to 7,3% for heating and 12,8% for cooling in the case of low-emissivity double glazing systems that fulfil the normative standards), because, compared with the case of Monopoli, they are here wider and less shaded to the solar gains.

In all, the assessment reveals that, beyond the fulfilment of the normative standards, the retrofitting strategies should focus on those components that mainly affect, due to their extent and exposition, the building consumptions, according to a performance-based approach, where further aspects, as discussed in the following sections, must be taken into account.

4.2 Building pathologies (C2)

Based on the direct investigation of the state of conservation of the buildings, some representative decay and failure patterns were ascribed to the models of tower-house in Monopoli and court-house in Maglie, respectively, in order to support the diagnosis of the relative causes (Fig. 18). Decay and failure patterns were mainly referred to humidity patterns and surface alterations, because, compared with crack patterns, they are much more consistent and connected to energy issues, in terms of both causes and remedies.

In detail, the model of tower-house in Monopoli is featured by humidity patterns on the roof and on the upper part of the external façade, with plaster detachments and stains. Such patterns are caused by the damage of the waterproof membrane either/or the wrong water outflow by the lightweight concrete inclined screed. The wooden frames of the windows are generally considered as decayed, due to vulnerability to environmental agents either/or poor maintenance. The wooden intermediate joists and boards are described as decayed, too, because of the high deformation under the service loads. Finally, rising damp humidity patterns are attributed to the basement and the lower part of the walls, with erosion of the exposed stone blocks. Here, the proximity to the sea is a critical factor, considering that the structures are directly in contact with the wet soil.

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The model of court-house in Maglie was assumed with some similarities to the previous case, with regard to the decayed wooden frames of the windows and the water infiltration on the roof and the upper part of the walls, toward both the street and the courtyard. However, the humidity patterns are here considered more severe, with evidence of mosses and lichens, due to the stagnant rainfall waters on the extrados profile of the roof vaults and to the characteristics of the "Carparo" tuff, which is highly hygroscopic, compared with the calcarenitic limestone. Such characteristics affect the rising damp, too, here less evident and only connected with the waters from the cistern and the contiguous street. Nevertheless, the exposed stone walls are highly affected by alveolization in the lower part, because the material is very friable, soft and salt-vulnerable. Finally, the courtyard is modelled as open space with wild vegetation due to lacking maintenance and the vault on the open atrium as decayed due to condensation humidity for missing thermal insulation.

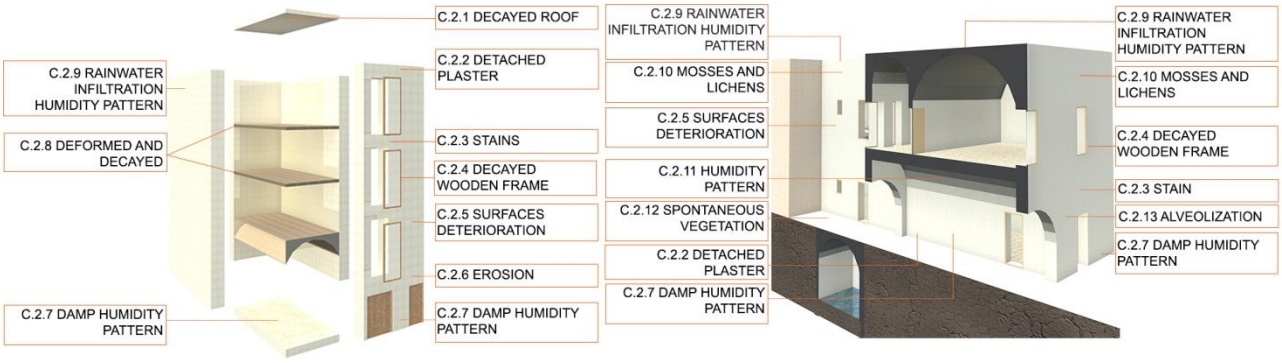


Fig. 18. Models of building pathologies in Monopoli tower-house and Maglie court-house

4.3 Inherent bioclimatic qualities (C3)

Based on the identification of the construction elements that might ensure passive regulation of air and heat in the case studies, the models describing the inherent bioclimatic qualities were developed (Fig. 19), in order to highlight the solutions to be preserved and integrated with HVAC systems for indoor quality control.

In detail, the model of tower-house in Monopoli is featured by compact shape, with only one façade on the outside, with narrow openings and low envelope transparent/opaque ratio. Such a configuration corresponds to limited heat-transferring surfaces, with relevant benefits in both winter and summer. Furthermore, the summer performances are guaranteed by the massive walls, which attenuate and shift the thermal wave due to their thermal inertia, as well as by the presence of vertical chimneys going from the ground floor to the roof that make the air circulate and exchange from the bottom to the top due to pressure and temperature gradients.

The model of court-house in Maglie is featured by some similar qualities, including the massive walls with high thermal inertia. Nevertheless, here, the presence of openings on opposite sides of the building, enhancing transversal ventilation, and the vegetation in the courtyard, providing temperature mitigation by shading and evapotranspiration, significantly

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enhance the summer performances. Furthermore, the core of the model is the courtyard itself, an archetype of the Mediterranean bioclimatic architecture. By day, the courtyard allows the air circulation across the indoor spaces due to the temperature differences between shaded and sunny areas, while, by night, it enhances the "chimney" effect of the hot air from the interior rooms. Finally, the model shows a system for collection of rainwaters from the courtyard and the roof into the underground cistern, which might allow optimal exploitation for irrigation and plumbing compatible uses.

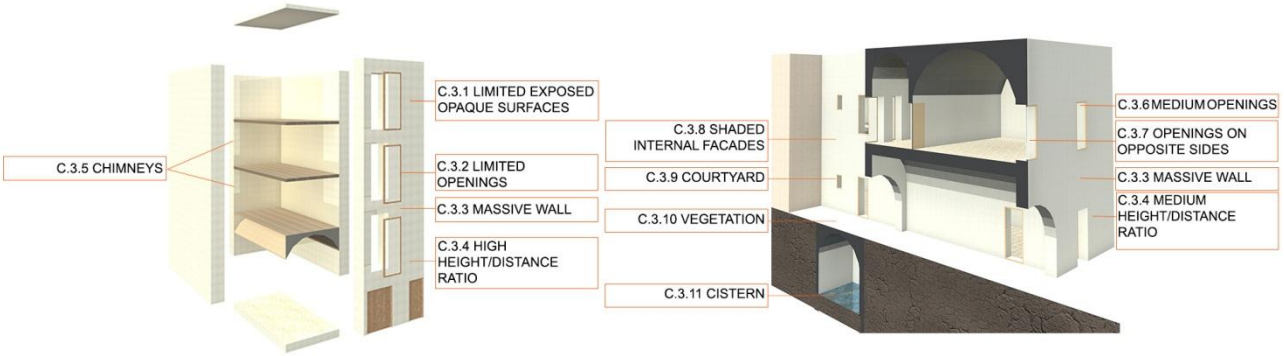


Fig. 19. Models of inherent bioclimatic qualities in Monopoli tower-house and Maglie court-house

4.4 Historical-architectural values (C4)

The identification of the elements featuring the material and formal identity of the buildings aimed at assessing the degree of transformability of the construction components (Fig. 20), toward compatible solutions that might enhance the values resulting from a long-lasting process of historical evolution.

In detail, the model of tower-house in Monopoli shows original stone tiles on roof and basement slab, wooden windows and main gate, exposed stone walls at the ground floor and plastered walls at the upper floors. Such features correspond to different retrofitting flexibility. The stone tiles might be removed and then placed back, in order to carry on some interventions on the relative components. Moreover, they might be covered by light, transparent, independent and reversible systems, given that morphology, texture and colour should be always visible (medium degree of transformability). The plaster coatings and the wooden windows might be replaced with more performing solutions, on condition that the thickness, the colour and the chemical-physical compatibility with the original structures are kept (medium degree of transformability). The exposed stone walls are more critical, since they cannot be replaced, temporarily removed or treated with surface coatings (low degree of transformability), also due to the presence of ornamental elements, such as coat of arms, decorations, stone lintels, where only cleaning and protection are allowed. Finally, the roof slab is a counter-value, considering that it is neither original nor compatible with the traditional architecture, so that even the replacement might be considered (high degree of transformability).

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The model of court-house in Maglie shows some of the above-mentioned values, including the ornamental elements, here even richer due to the building typology, with decorated gates, lintels, cornices and stringcourses. As far as the construction components are concerned, the main values are ascribed to the exposed stone walls, the typical "star-shaped" vaults decorated with frescoes and temperas, as well as the stone tiles on roof and basement slab. In this case, same remarks might be pointed out for exposed stone walls and decorated plasters (low degree of transformability) and stone tiles (medium degree of transformability).

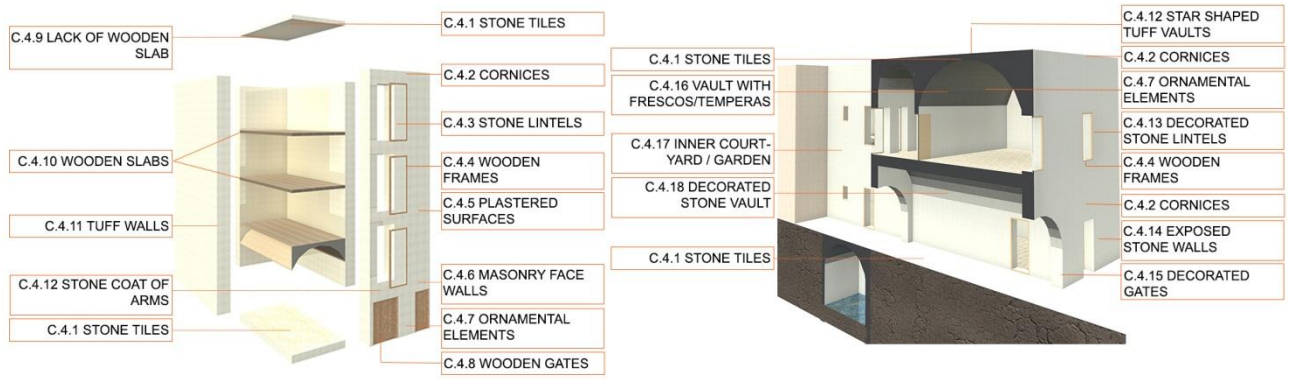


Fig. 20. Models of historical-architectural values in Monopoli tower-house and Maglie court-house

5. Transformation versus conservations: suitable strategies (D) and technological solutions (E)

The assessment of the models of tower-house and court-house concerned energy deficits and building pathologies, on the one hand, and bioclimatic qualities and architectural values, on the other hand, in order to identify suitable strategies for the performance improvement of the buildings through conservation and enhancement of their original characters. In detail, according to the methodology as in paragraph 2, all the above-mentioned aspects should merge in a multicriteria analysis of the possible solutions reported in the general atlas, according to the Analytic Hierarchy Process (AHP) and based on the identification of the indicators and the assignment of weights and scores by a panel of experts through the Delphi method. The analysis should take into account compatibility; performance-technical reliability, environmental life cycle assessment and cost/benefit analysis, in order to identify suitable technological solutions.

In the case of the tower-house, the comparative assessment of the models (C1, C2, C3,C4) has identified the roof as the construction component with the highest improvement potential. In fact, the increase of its thermal resistance would result in the greatest heating and cooling savings (about 33% and 30% respectively in case of normative fulfilment). Nevertheless, its retrofitting is also required to prevent the rainwater infiltration through replacement of the decayed waterproof membrane and replacement/repair of the lightweight concrete inclined screed. Finally, the intervention on the construction components is flexible due to the presence of non-original concrete slab and removable stone tiles (high degree of transformability).

Consequently, possible technological solutions (code E1 for roofs) might be:

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E1.a. Replacing the inclined screed above the slab with high performing insulation lightweight concrete (e.g., with expanded clay, pumice, expanded glass);

E1.b. Adding an high performing insulation panel above the screed, in order to achieve the lowest thickness increase (e.g. aerogel, VIPs, multi-layer reflective boards);

E1.c. Replacing the waterproof membrane, where the previously removed stone tiles should be installed on levelling concrete mortar;

and eventually:

E1.d. Adding coatings or boards with phase changing materials on the internal side to enhance attenuation and time shift of the summer temperature peaks through controlled latent heat storage and release (e.g. pre-cast PCM boards or PCM-embedded thermal plaster).

In addition to the roof, the further construction component that might be selected for energy retrofitting in the tower-house is the external wall, which would mostly affect the heating savings (up to 18% in winter against 6% in summer) and require some complementary interventions against the rising damp. Nevertheless, the remedies should take into account that the exposed stone surfaces cannot be modified (low degree of transformability) and the plastered surface should be replaced with similar colour and thickness (medium degree of transformability). Furthermore, the inherent thermal inertia of the walls should be preserved.

Consequently, possible technological solutions (code E2 for walls) might be:

- for plastered walls

E2.a. Adding high performing insulation panels on the external façade in order to achieve the lowest thickness increase (e.g. aerogel, VIPs, multi-layer reflective boards), including a thermo-insulating plaster coating (e.g. hydraulic lime with EPS additives).

- for exposed walls

E2.b. Filling up the inner cavity with high performing insulation mixtures (e.g. hydraulic lime with nanoparticles).

It is worth underline that the insulation on the internal facade of the walls has not been considered, in order to keep the thermal inertia of the component and prevent interstitial condensation.

In the case of the tower-house, the other construction components are not considered relevant. Particularly, the windows, due to their limited extent, provide with a limited contribution to the building consumptions, so that their replacement should be carried out only if they are decayed. Concerning the basement slab, the thermal insulation seems to worsen the energy performances, especially in summer. Consequently, the intervention should mainly focus on the rising damp, through separation of the structures from the wet soil by a horizontal non-ventilated cavity that would reduce the abutting surfaces and still make the indoor space benefit from the thermal inertia of the soil.

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In the case of the court-house in Maglie, the roof is again the component with the highest improvement potential, in terms of heating and cooling savings (about 33% and 30% respectively in case of normative fulfilment). Thus, the above-mentioned remedies might be applied (solutions E1.a-b-c-d), taking into account the need to keep the curve profile of the extrados (medium degree of transformability).

Differently from Monopoli, the further components that should be retrofitted are here the windows. In fact, the replacement of the existing transparent envelope with low emissivity double glazed systems would enable similar savings compared with the thermal improvement of the walls (7% against 11% in winter and 13% against 7% in summer). Nevertheless, such a replacement is also required by the need to overcome their obsolescence and the impact on the original features (medium degree of transformability) is much more advantageous than for the exposed walls (medium degree of transformability).

Finally, in the case of Maglie, the remarks on the basement slab and the interventions (solutions E2.a-b) on the plastered walls might be extended, even if they are considered less relevant for the overall building requalification.

It is worth underline that all the proposed interventions refer to construction components with high and medium degrees of transformability (see section 4.4) and they involve low impact on the historical characteristics, in terms of original architectural and technical identity of structures and spaces.

As an example of the achievable improvements, the results of some ex-post simulations are shown in Fig. 21 that refer to the retrofitting of the two most relevant components in both models, as previously outlined.

Particularly, in the case of Monopoli, two retrofitting combinations are reported:

- Retrofitted “tower-house 1” (52,6% heating and 35,80% cooling savings). The roof is composed of existing slab, 40mm thick aerogel board (λ=0,017 W/mK), lightweight concrete inclined screed, waterproof membrane, leveling concrete mortar and original stone tiles, while the plastered wall is retrofitted by replacement of the existing outer 40mm thick coating with 30mm thick aerogel board (λ=0,017 W/mK) covered by 10mm thick thermo-plaster;
- Retrofitted “tower-house 2” (53% heating and 38% cooling savings), where the previously described solutions are combined with 30mm thick PCM-embedded plaster (λ= 0.7 W/mK, $T_{transition}$= 25 °C) on the internal side of the roof concrete slab.

In the case of Maglie, only one retrofitting combination is reported:

- Retrofitted “court-house 1” (35,8% heating and 44,63% cooling savings). The roof is retrofitted as in the case of tower-house 1 above the bearing structure, while the windows are replaced by wooden frames and double-glazing units (3 + 13 + 3 mm) with low-emissivity treatment.

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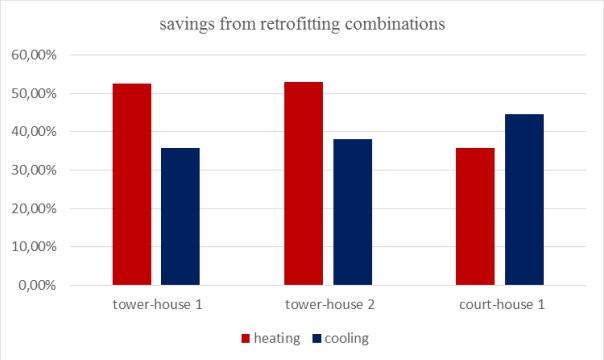


Fig. 21 Energy savings from different combinations of retrofitting solutions

Furthermore, the above selected combinations involve a significant reduction in CO_2 emissions, namely 13,8% for tower-house 1, 14,6% for tower-house 2 and 22,1% for court-house 1".

Finally, from the economic point of view, the solutions show quite similar initial costs, e.g. € 303,00/m^2 for the tower-house 1 and €384,00./m^2 for the court-house 1. The costs were estimated based on regional official price lists [36] [37], as well as on the market prices in 2016. Moreover, the pay-back time was calculated based on the cost of the saved energy, as provide by the Italian Energy Authority, as well as on the tax credit on the 65% of the initial costs for the first 10 years, according to the currently available Italian incentives. As an example, for tower-house 1, the payback time is 22 years, whereas for court-house 1, it is 19 years.

It is worth underline that, although quite high, the above-mentioned values are likely to decrease quickly, considering that the involved innovative products will tend to gain technological maturity and, thus, economic competitiveness.

6. Conclusions

The proposed methodology for energy assessment and retrofitting of historic districts of the coastal and sub-coastal towns of South Italy is focused on some key-concepts, which the operation aspects derive from:

- Local action, in order to target diagnosis methods/tools and intervention measures/remedies on the specific environmental, architectural and construction features of the geocluster and, thus, prevent from the "tout-court" application of solutions and systems from different contexts with ineffective, even inadequate, results.
- Unitary vision, which considers the built heritage as a complex system, with different levels, from the site to the district, from the building to its components, in order to neglect a "case-by-case" approach and define assessment and control scenarios that might be replicated according to a coordinated and integrate actions from the fabric to the urban settlement.
- Performance-based approach, where pre-design characteristics and behaviours are identified as guidelines and best practices, before the selection of specific solutions and products that are typically temporary due to the technological and commercial evolution.

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- Multi-disciplinary coordination toward integrated conservation, where energy retrofitting is part of a synergic framework, including building refurbishment and urban regeneration.

As far as the case studies are concerned, the application of phases and tools from such key-concepts enabled, from the extended and diffused analysis of the context, to derive some models describing the aspects that mostly affect the selection of suitable energy retrofitting measures. In fact, the assessment of energy deficits and building pathologies that determine the need for transformation, on one hand, and the critical reading of bioclimatic qualities and historical-architectural values that identify the need for conservation, on the other hand, allowed to identify the domain in which interventions can be effective and compatible. Nevertheless, such interventions, albeit more limited compared to fields with higher levels of design freedom, might ensure a significant improvement of the current state as balanced goals between prescriptive accomplishment and acritical exception of the normative standards.

It is worth mention that the results, beyond scientific and technical impacts, have relevant implications at the political and management levels, toward the development of decision-making support tools for the identification of priority interventions and the development of funding programs by the local authorities in charge for the safeguard of the landscape and the heritage.

Finally, it should be outlined that the actual implementation of the proposed solutions must take into account some barriers, namely private ownership of the buildings and higher costs for specialized labour. Nevertheless, it could benefit from the rapid reduction of costs throughout the time for innovative products, following their technological maturity and, thus, economic attractiveness.

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